TWO IDEAS OF THE REDOX REACTION: MISCONCEPTIONS AND THEIR CHALLENGE IN CHEMISTRY EDUCATION

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ABSTRACT

In interpretations of chemical phenomena students like to mix the macro level of substances with the sub-micro level of atoms, ions and molecules: "water boils at 100 ^{o}C and has an angle" – instead of separating properties of substances (water has a special density, freezing- and boiling point) and properties of particles (the H_2O molecule has an angle, H and O atoms are linked by electron-pair bond). For redox reactions students are doing this too: "one Cu^{2+} ion takes two electrons and is reduced to copper" – instead of "to one Cu atom"! Another difficulty seems to be the historical redox definition with the "oxygen transfer": this idea is so attractive that students argue mostly with oxygen participation instead of the transfer of electrons. This article reflects those misconceptions and proposes ways of instruction to prevent from "school-made misconceptions". *[AJCE, 2(2), February 2012]*

INTRODUCTION

In modern chemistry education the redox reaction is defined by an electron transfer, as illustrated with a metal-nonmetal reaction (see Fig. 1), or with the reaction of iron and a copper sulfate solution (see Fig. 2).

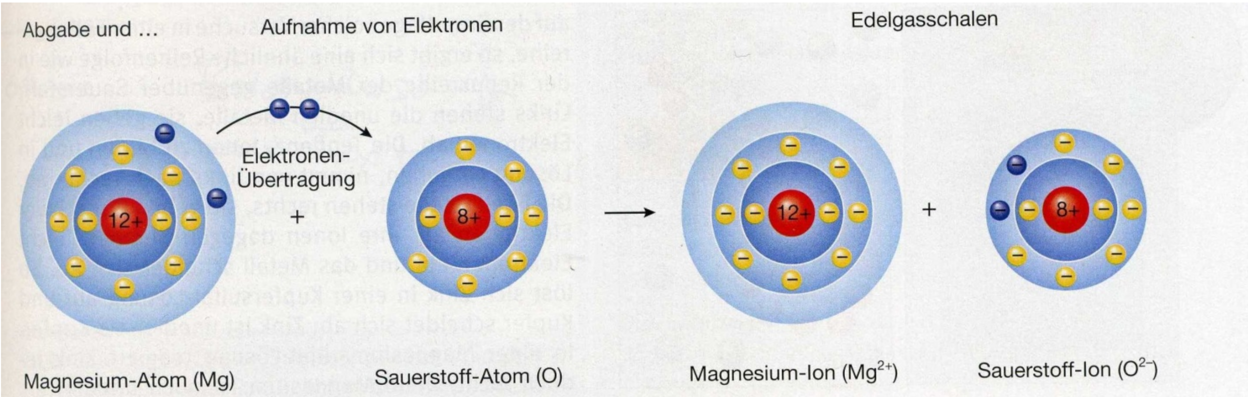


Fig. 1: Model of the reaction of metal atoms with nonmetal atoms by electron transfer (1)

In these examples, the reactions can be explained by electron transfer from metal atoms to nonmetal atoms or of metal atoms on metal ions – it is correctly argued with involved atoms and ions (see Fig. 2):

Oxidation: Fe atom $\rightarrow$ Fe^{2+} ion + 2 e^-
Reduction: Cu^{2+} ion + 2e^- $\rightarrow$ Cu atom
Redox: Fe + Cu^{2+}(aq) $\rightarrow$ Cu + Fe^{2+}(aq)

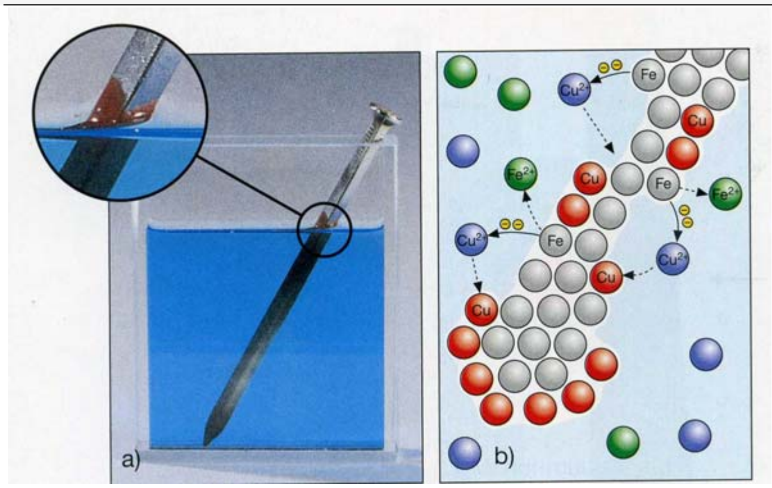


Fig. 2: Photo of the reaction of an iron nail with copper sulfate solution, model drawing of the particle view (1)

One other example presents the reaction of potassium iodide solution with bubbles of chlorine gas. The model drawing (see Fig. 3) shows that Cl_2 molecules are reacting with $I^-(aq)$ ions to form I_2 molecules and $Cl^-(aq)$ ions. Electrons are moving from $I^-(aq)$ ions to Cl_2 molecules (see Fig. 3), all $K^+(aq)$ ions are spectator ions: they are not involved in the reaction (2).

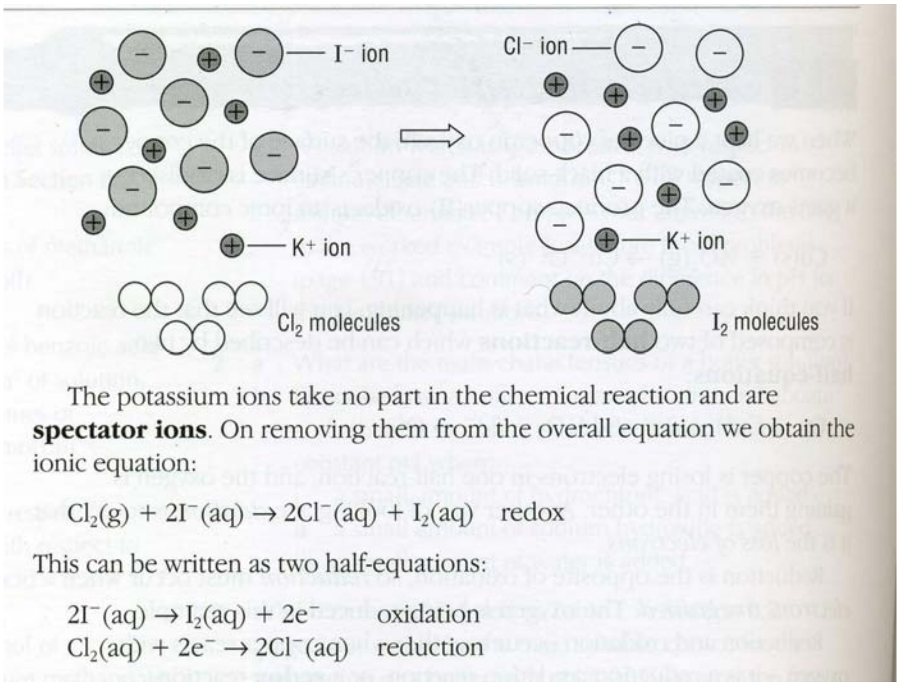


Fig. 3: Model drawing of the reaction of Cl_2 molecules with $I^-(aq)$ ions, $K^+(aq)$ ions remain as spectator ions (2)

If you ask, however, freshmen students at the beginning of their studies in chemistry, one is astonished that mostly the iron-copper sulfate experiment is not reflected on the basis of atoms and ions but of substances: "copper is oxidized to copper oxide and is deposited on the iron nail; iron is oxidized and copper sulfate is reduced; iron is oxidized and takes O from the $CuSO_4$; electrons are released and oxygen is absorbed" (questionnaire before the lecture in the summer term 2011 at University of Muenster, Germany). On the one hand – rather than with atoms or ions – the students are arguing with substances such as iron and copper sulfate, on the other hand with oxygen in the sense of the historical definition by Lavoisier in 1784. This first definition of redox processes is so attractive that many learners seek to explain those reactions by oxygen transfer: "O is taken out of $CuSO_4$"

This paper addresses the question of misconceptions according to the two well known redox definitions and tries to analyze and to compare those erroneous answers. The second part of the paper proposes ways in chemistry education, which should ensure some prevention and challenge regarding the existence of misconceptions (3).

MISCONCEPTIONS AT THE END OF SECONDARY EDUCATION

In lessons at the primary level the children are bringing a lot of good observations (3): concerning combustion processes they state: "the fuel disappears irretrievably; some things go into the air (phlogiston?); candles burn totally away; coal glows and leave some ashes behind" (3). Instructing gases and their properties children talk about "gases weigh nothing; even hot air rises up, water evaporates and changes to air; gases are necessary for cooking and heating; gases may explode" (3). Despite good observations, children will not grab the scientific idea without the teacher; they will stay with their *preconcepts*, with their *alternative concepts* from everyday life. The teachers must know those who have preconcepts have to perform good experiments concerning mass comparison of metal and metal oxide portions, should show the density of various gases to help children to change their concept, to realize a "conceptual change" (4). Many other preconcepts concerning combustion, chemical reactions, gases, light, heat, changes of state or particulate nature of matter are described and discussed by Rosalind Driver (5) and Vanessa Kind (6).

Since neither the young people know the historical approach to the explanation of combustion processes by oxygen transfer in oxidation-reduction reactions nor they know from everyday life the concept of electron transfer in redox reactions, a good instruction on these topics should be successful to grab those scientific ideas. Empirical surveys now show, however, that one can find "*home-made misconceptions*" or "*school-made misconceptions*" (4). After an analysis and the knowledge of such ideas, it should be possible to design teaching ways or actions that propose prevention against known misconceptions and convey scientific concepts successfully. Some examples of misconceptions should be referenced. Other *misconceptions* about basic chemical ideas can be found in articles of Vanessa Kind (6) and Keith Taber (7).

Redox and oxygen transfer. In many curricula of schools the oxygen transfer is instructed as the first central idea concerning combustion processes and the participation of oxygen. Hans-Jürgen Schmidt (8) interviewed several thousand students of secondary education, which one of the following reactions should be a redox reaction:

(i) $2\,HCl + Mg \rightarrow MgCl_2 + H_2$
(ii) $2\,HCl + MgO \rightarrow MgCl_2 + H_2O$
(iii) $2\,HCl + Mg(OH)_2 \rightarrow MgCl_2 + 2\,H_2O$

About half of the students in grades 10 – 12 chose the correct answer (i). The remaining participants were not sure about this and chose the reactions ii or iii or both (that are acid-base reactions!), and delivered reasons such as: "MgO and $Mg(OH)_2$ contain oxygen, what is absolutely necessary for redox reactions; to any redox reaction O is necessary – so choice (i) cannot be a redox reaction". These students include the syllable "ox" on the participation of oxygen (8) – even if the electron transfer was taught in classes and the oxygen reaction has been declared as a special case of redox reactions.

Iron-copper sulfate reaction. Elke Sumfleth (9) examined statements of students in grades 6-13 made to the well known reaction of an iron nail in copper sulfate solution. She documented a lot of wrong answers, which were based on preconcepts and school-made misconceptions. Above all, students in grades 6 to 8 described the emergence of a copper-colored coat with "settling, hanging or sticking or staining a substance on the iron nail". Interpretations related to every day life are: "copper sulfate colors the iron nail; copper sulfate sticks on the nail; it stuck, it glues on the nail like color on a piece of wood and then dries up"(9). Half of the seventh-graders suspected an attraction as the cause of the red substance; other students mention an existing magnetism – probably because of the iron nail. These young students just described their observations in other words – you cannot expect scientific ideas.

However, even on the advanced level in grade 10 – 12 there are misconceptions – only interspersed with specialized scientific terms: "copper dissolves from the sulfate and binds to the iron; copper sulfate is reduced; copper atoms attract electrons; iron nails can absorb the ionic solution" (9). These statements demonstrate that special terms of the scientific terminology are indeed learned and the students feel the urge to use them well.

According to the redox idea Vitali Heints (10) developed a new instrument and presented a 15-question questionnaire to students in grades 10 - 12 in some schools of the area of Muenster in Germany. From that questionnaire three problems are taken as examples for this article.

Task 1
An iron nail is dipped into a copper sulfate solution. After one minute, a copper-colored coat is deposited on the nail. Explain the observation.

A total of 34 % of participants used the terms redox reaction (oxidation, reduction) and electron transfer, 14 % used the terms ignoble and noble metals. Most students took common reaction equations to illustrate the reaction, but they were usually not correct. A large number of correct answers was built along the same line: "copper is more noble than iron, since copper is firmly set on the iron nail, this means that Cu^{2+} ions from the copper sulfate solution were reduced, copper was formed by a redox reaction".

More than 60 % of responses were classified as defective. In many cases, students do not distinguish between on the one hand, copper and copper sulfate (solution), on the other hand, not substances and particles: "copper ions from the solution connect with the iron nail". Some students of grade 10 were thinking that the metal coating is rust: "the copper-colored material is rust; iron is attacked and there is rust; the nail rusts through the immersion into the copper sulfate solution". Others see the process and result in no reaction as the cause of attraction or in a magnetic interaction: "the nail is magnetic and attracts the sulfate; the copper from the solution is magnetic as the nail".

A "staining, settling or sticking of elemental copper, of the copper sulfate solution, of copper atoms, of copper ions or copper electrons" is suspected in many answers: "the copper particles are deposited on the surface of the nail; copper sulfate solution is saturated and combines with iron atoms on the nail; copper electrons are deposited on the nail and the coating is formed" (10). The data analysis shows that about half of the students are describing their observations by use of familiar every day language.

Students in grades 10 – 12 really show school-made misconceptions, because they do not distinguish between ions and atoms, between atoms or ions and related substances: "copper sulfate is reduced and becomes copper and iron; copper ions from the solution connect with the iron nail; iron (Fe) reacts with copper sulfate ($CuSO_4$) and by a redox reaction, the iron takes electrons from $CuSO_4$ and becomes copper-colored" (10).

For some students it does not seem to be clear that for the emergence of elemental copper, a redox reaction is necessary – in their minds copper is already present in the form of the element: "copper from copper sulfate solution is deposited on the iron nail, it will combine with iron atoms". The idea of existing ions in salt solutions is missing; those students are mixing substances like copper, copper sulfate solution and iron with their atoms or ions.

Metal-oxygen reactions. This second task is determined to show how students describe their ideas on metal-oxygen reactions. In particular, we want to know whether the simple oxygen-definition or the enhanced electron transfer theory is used by the young people, in what cases and to what extent they argue with substances or with atoms, ions or molecules.

Task 2

A piece of copper sheet is folded to a small envelope and heated with the roaring flame: the outside of the sheet turns black, after opening the envelope the inside remained copper-colored.

O a combustion reaction takes place, [A]
O the outside is made from black soot, [B]
O a redox reaction occurs, [C]
O copper atoms change their color. [D]

Explain your answer.

With 59 % of markings the destructor [B] was the most attractive choice, only 21% gave the right answer [C], [A] and [D] were chosen by 18 % and 4 %. The popularity of destructor [B], which was combined to a large extent with [A], sometimes with [C], is probably due to the lack of practical experimentation – apparently, many students don’t know the "roaring flame" and what it means. The reasons given for [B] are as follows: "by the flame / through combustion / fire is formed soot, burns outside the copper plate, copper oxidizes, the soot is copper oxide".

Also the role of oxygen for the combustion is not clear for young students, they are looking for everyday life explanations: "oxygen is burned and soot is deposited; oxygen is burned and carbon dioxide is produced, the combustion leads to three products: CO, CO_2, C ". When the advanced students have chosen the right answer “redox reaction”, so they didn’t have outlined any electron transfer or equations partly for electron release and electron acceptance.

Task 3

For the production of iron in the blast furnace iron oxide (Fe_3O_4) and coal (C) are necessary, by heating the mixture strongly, the liquid iron is running out with glaring light.

O carbon is a catalyst, [A]
O a redox reaction takes place, [B]
O iron oxide is reduced, [C]
O iron oxide decomposes into elements. [D]

Explain your answer.

Blast furnace process. This task describes the production of iron through the reduction of iron oxides by coal, which is well treated in nearly every chemistry instruction. The response pattern is characterized by an almost equal percentage distribution of answers; the correct answer [B] was only given by 20 % of the students, a sufficient explanation by only 4 %. By their explanations almost nobody argued with electron transfer, but usually with “oxygen transfer” and equations in words, or (often completely wrong) with reaction equations and the “change of O atoms” like in this equation: $Fe_3O_4 + 2\ C \rightarrow 3\ Fe + 2\ CO_2$.

Other reasons are: "coal reacts with oxygen from iron oxide to form CO_2, iron is left; by the carbon combustion oxygen is needed, which is taken from iron oxide". Mostly the answer [A] was chosen and justified as follows: "carbon only helps to get the reaction going, but it does not react; carbon supplies the heat that is necessary for the decomposition of iron oxide" (10).

PREVENTION OF HOMEMADE MISCONCEPTIONS

According to the poor results by teaching the redox idea one likes to state: "disregard the simple redox idea of oxygen transfer from school curricula and school books". Considering that in so-called oxygen-transfers – for example in the reaction of copper oxide with iron – oxygen atoms are not transferred, but iron atoms release electrons to copper ions and the oxide ions change only the ionic lattice, so the emphasis on "the oxygen" is not justified: neither oxygen is transferred, nor O atoms change their partner. If the redox idea would only be taught as an electron transfer from one particle to another, then instruction and results should improve dramatically.

Historical redox idea. Since this idea is prescribed in all guidelines and school books, one must consider ways of instruction that are touching the extended redox idea as little as possible. There is first the historically evolved definition: teachers or students can refer Stahl's Phlogiston theory from 1690 and its refutation by the Oxidation theory of Lavoisier in 1784. Students can understand that historically adapted theories have been rejected later and replaced or extended by new theories. In their own classes, they can accept that the extension of the "oxygen transfer" to the electron transfer is legitimate.

On the other hand, in the beginning one could instruct this subject without the word "redox" and use it only in the extended sense. Since oxidation (metal + oxygen → metal oxide) and reduction (silver oxide → silver + oxygen) are initially defined separately, the redox idea appears dispensable; the notation for the copper oxide-iron reaction is sufficient in this way: iron is oxidized to iron oxide, copper oxide is reduced to copper. Then, if the reaction is described only in words, one cannot get into difficulties with "O atoms, O_2 molecules or O^{2-} ions are changing the partner". Choosing a model drawing to show the regrouping of "particles" in the copper oxide-carbon reaction for example, you can explain the "combination of carbon particles with the oxygen particles and the release of copper particles" (Fig. 4).

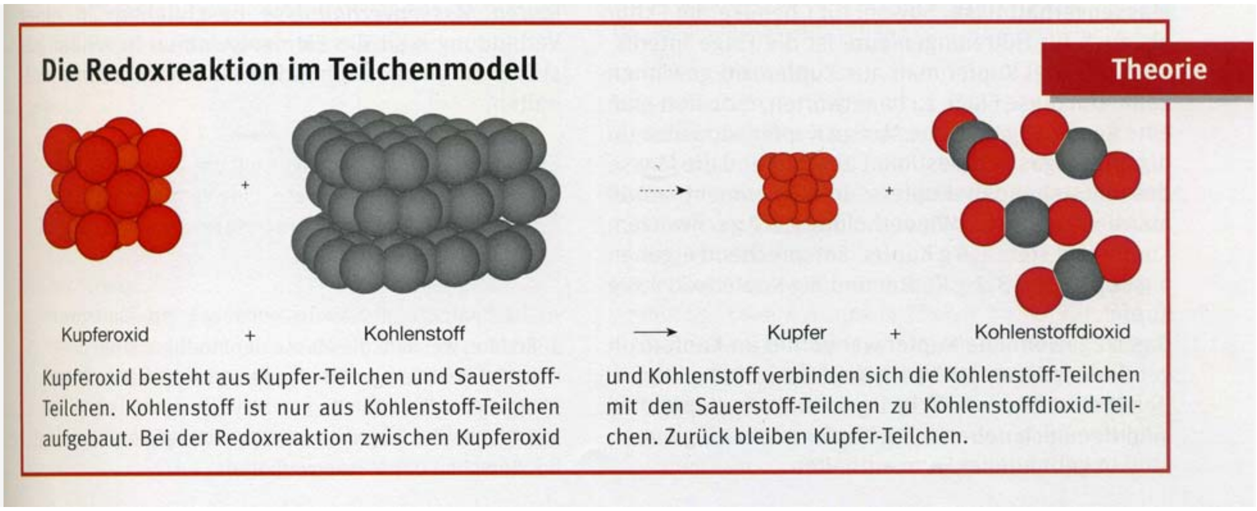


Fig. 4: Model drawing for the reaction of copper oxide with carbon (1)

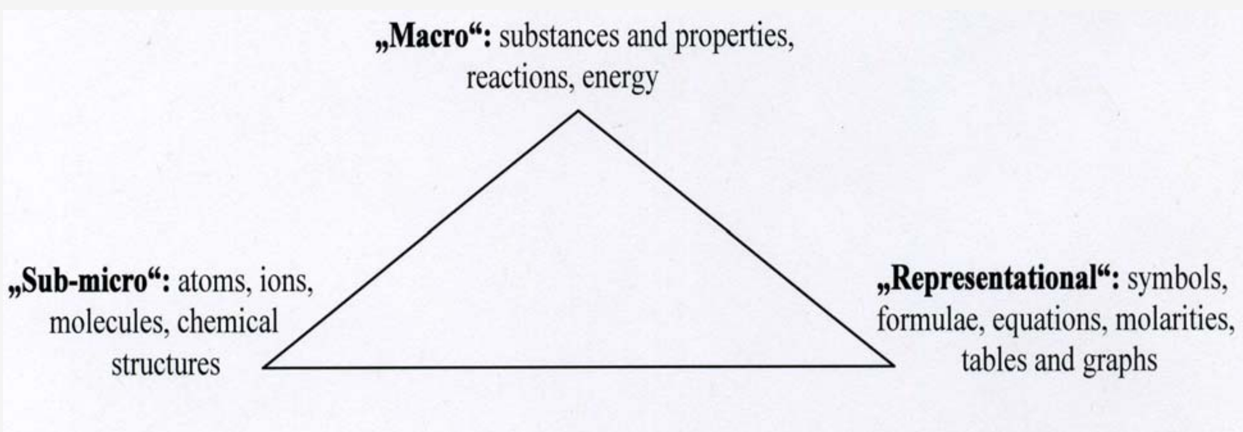


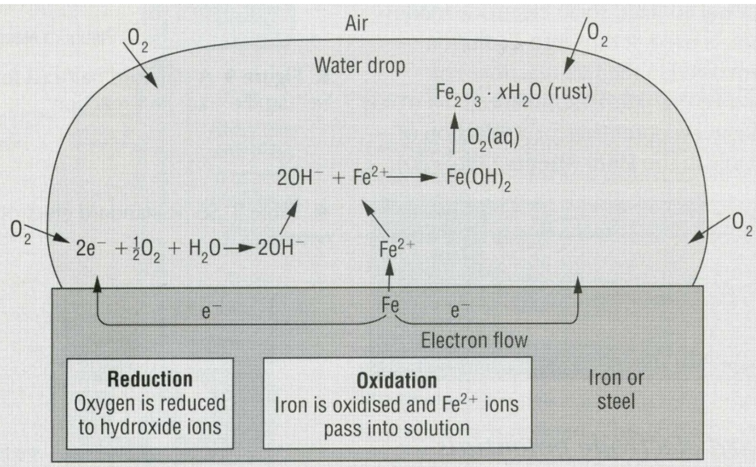
Fig. 5: Macro, sub-micro and representational level in chemistry education (11)

Extended redox idea. Successful teaching is possible if the arguments regarding the substances, the smallest particles and the chemical symbols are distinguished from each other. Johnstone (11) created his “chemical triangle” (see Fig. 5) to propose three levels of interpretation: “We have three levels of thought: the macro and tangible, the sub-micro atomic and molecular, and the representational use of symbols and mathematics. It is psychologically folly to introduce learners to ideas at all three levels simultaneously. Herein lay the origins of many misconceptions. The trained chemist can keep these three in balance, but not the learner" (11). Specially Gabel (12) points out that teachers like to go from the macro level directly to the representational level and that students have no chance to follow this concept: "The primary barrier to understanding chemistry is not the existence of the three levels of representing matter. It is that chemistry introduction occurs predominantly on the most abstract level, the symbolic level" (12).

If we take into consideration that for the extended redox idea all arguments should be done exclusively by atoms, ions or molecules (Fig. 1 and 2: the metal atom emits two electrons, the non-metal atom or the copper ion takes two electrons), and follow all chemistry teaching though the Johnstone-Gabel demand, we may have a better teaching success. Perhaps even model drawings should be drawn by the learner (Fig. 2), and in the first step the names "atom" and "ion" should be involved:

oxidation: Fe atom $\rightarrow$ Fe^{2+} ion + $2e^-$
reduction: Cu^{2+} ion + $2e^-$ $\rightarrow$ Cu atom
redox: Fe atom + Cu^{2+} ion $\rightarrow$ Cu atom + Fe^{2+} ion

After pointing out that not the substances are described by those reaction equations, but the involved atoms and ions, one can change to write those equations without mentioning the names "atom" and "ion" all the time. Another example for writing redox equations and drawing a model picture is the formation of rust by the reaction of iron, water and oxygen (see Fig. 6).



◄ **Figure 11** Rusting is an electrochemical process.

The concentration of dissolved oxygen in the water droplet determines which regions of the metal surface are sites of reduction and which are sites of oxidation. At the edges of the droplet, where the concentration of dissolved oxygen is higher, oxygen is reduced to hydroxide ions.

$\frac{1}{2}O_2(g) + H_2O(l) + 2e^- \rightarrow 2OH^-(aq)$

The electrons needed to reduce the oxygen come from the oxidation of iron at the centre of the water droplet, where the concentration of dissolved oxygen is low. The Fe^{2+}(aq) pass into solution:

$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$

The electrons released flow in the metal surface to the edges of the droplet.

Fig. 6: Model drawing of most involved particles in the formation of rust (2)

The same is true for acid-base reactions by Broensted (4): not the substance hydrochloric acid is the acid in accordance with the modern definition, but the H_3O^+(aq) ions are the acid particles. In pure sulfuric acid the H_2SO_4 molecules are declared as acid particles, but in diluted sulfuric acid, the H_3O^+(aq) ions and HSO_4^-(aq) ions should be the acids. So if we argue about this issue not with substances but with acid particles and base particles, students can look consequently to all involved particles of an acid-base reaction and can decide successfully which particle is the acid and which particle is the base in the sense of Broensted. Those interpretations would fit to the "Chemical Triangle" – and students would comprehend modern chemistry.

CONCLUSION

A decision has to be made if the known misconceptions should be included in the classroom lecture to maximize the teaching success. Marco Oetken and Karin Petermann (13) instructed the combustion processes in grade 8 in the way that a cognitive conflict arises. After discussing the alternative concepts concerning combustion, they filled a round flask with a few carbon pieces and with oxygen, and weighed the closed flask on a good balance. Then they heated the flask as strong as possible, the carbon pieces started to burn, and vanished by shaking the flask. After cooling down the flask they could show with the balance an equal mass as before and explained it with the reaction of carbon and oxygen to carbon dioxide (lime water test was made). Finally the carbon-oxygen reaction was shown by model drawings and word equations (see Fig. 4). With those experiments they tried to reach a "conceptual change" in the cognitive structure of their students. They came back to the preconcepts and compared the new scientific model of the carbon-oxygen reaction with all the alternative concepts of the students: "carbon disappears, carbon is gone and the flask weighs less than before”. By including those comparisons Oetken and Petermann are convinced that a "conceptual change" will be more successful than without those discussions.

Fig. 7: Concept cartoon concerning conservation of mass by rusting processes [13]

What is the reason that an iron nail turns red-brown in a solution of copper sulphate?

Fig. 8: Concept cartoon concerning the iron – copper sulfate reaction

Tobias Doerfler (14) taught the topic acids and bases in grade 11, he introduced the neutralization with "beaker models" for hydrochloric acid and for sodium hydroxide solution: H_3O^+(aq) ions and Cl^-(aq) ions on one side, and Na^+(aq) ions and OH^-(aq) ions on the other side. At the end the students described the neutralization with the equation:

$$H_3O^+(aq) + OH^-(aq) \rightarrow 2\ H_2O;\ \text{exothermic}$$

He pointed out that there is no formation of salt or salt solution, that the other ions are staying unchanged; they may be called "spectator ions". Finally he took the well known misconceptions into focus and gave one group the incorrect mental model of "HCl molecules in hydrochloric acid, NaOH molecules in sodium hydroxide solution, a salt formation by the neutralization" (14). The students took those statements and corrected them in the sense of the new gained scientific concept; they applied the new concept to unmask those models as misconceptions. In a second test after working with those misconceptions the results of the test were better than without those discussions (14).

Another way to integrate misconceptions and their correction into lectures is the introduction of *concept cartoons* (15). Temechegn Engida and Sileshi Yitbarek (16) created those cartoons relating to many topics of chemistry education. Two examples are printed out: with the question according to the masses of an iron nail before and after rusting completely, one student is giving the right answer, three other students are stating wrong mental models (see Fig. 7). For the iron-copper sulfate reaction three persons are telling misconceptions, only one person gives the right answer (see Fig. 8). Students can discuss all answers, should find the right answer, and should correct the three mistakes. Concept cartoons can be presented before starting a topic to diagnose the misconceptions of the students in class: then the teacher knows the ways how his students are thinking, he knows which knowledge exists for starting the topic. The cartoon should also come into discussion at the end of the topic to summarize the new gained scientific knowledge and to state clearly what is wrong with the presented misconceptions and what is right.

The end. The terms oxidation, reduction and redox reactions are central for understanding chemistry – they must be taught best. With the redox idea young people can interpret a lot of everyday life phenomena: combustion phenomena, the rusting of iron and other corrosion processes, the production of iron in the blast furnace, the electrolysis of aluminum oxide melt for aluminum production, the production of electrical energy from batteries and accumulators.

This is to proceed in two steps. In the first step in beginning of teaching burning processes the concepts of oxidation and reduction on the level of oxygen transfer are possible, *substances* are oxidized or reduced. The reactions should experimentally be shown and can be described in word equations and model drawings (see Fig. 4), but not in formulas. One may also think about the term "redox" – it may be omitted in this context.

In the second step, in advanced lectures, the extended redox idea should be taught. With the word "redox" the electron transfer is linked and described by *particles*: metal atoms are oxidized to ions, other ions are reduced to atoms. Part equations for oxidation and reduction should show the number of transferred electrons, model beakers or model drawings may visualize those chemical processes (see Fig. 2 and 3). With the sequence "macro → sub-micro → symbolic" (see Fig. 5) not only redox reactions can be taught successfully, also acid-base reactions and complex reactions! And don't forget to integrate misconceptions into lectures: the students know with those discussions what is right and what is wrong!

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